Zenodo (March 2026)
DOI: 10.5281/zenodo.19438613

Advances in Wastewater Treatment: Energy Efficiency, Micropollutants, and Circular Resource Recovery

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Abstract

The field of wastewater treatment is evolving from conventional organic load removal towards integrated, multi-barrier systems that address nutrients, pathogens and emerging micropollutants [11,12,14]. This review evaluates current treatment strategies, from activated sludge and biological nutrient removal to advanced oxidation processes, membrane technologies, and hybrid systems, focusing on performance, operational complexity, and energy demand. Tertiary or quaternary interventions are required for persistent contaminants, including pharmaceuticals, endocrine-disrupting compounds, and PFAS, which are widely detected in surface waters at trace concentrations and may exert ecological effects even at very low levels [11,30]. Emerging approaches such as hydrodynamic cavitation, photocatalysis, microbial fuel cells, forward osmosis, cold plasma, and controlled-release oxidants are assessed for their feasibility, scalability, and potential for integration. Regulatory frameworks in the European Union and the United States are increasingly driving the adoption of advanced treatment processes and circular resource recovery strategies. The analysis emphasises the importance of coordinated system integration, digital process optimisation and energy recovery in order to achieve sustainable, energy-efficient and high-quality effluents. The next generation of wastewater treatment plants is envisioned as a hub for resource recovery and water reuse, combining biological, physicochemical and digital solutions to meet increasingly stringent effluent standards while minimising environmental and economic costs. This synthesis provides a roadmap for implementing innovative, regulatory-compliant, circular wastewater treatment strategies [6,7] in a rapidly changing environmental and technological landscape.

Keywords: wastewater treatment, advanced oxidation, micropollutants, membrane technology, energy efficiency, circular economy, regulatory compliance, hybrid systems.

1. Introduction

Wastewater treatment is essential for protecting public health [1,5], preserving aquatic ecosystems and ensuring the sustainable management of water resources. The rapid growth of urban areas, the expansion of industry, the increasing presence of emerging contaminants and the introduction of stricter regulatory frameworks have transformed wastewater treatment plants (WWTPs) from conventional pollution control facilities into advanced multi-barrier systems that integrate treatment and resource recovery functions. Discharging untreated or inadequately treated wastewater contributes to oxygen depletion, eutrophication, toxic contamination and pathogen transmission in receiving waters [1,13]. Depending on the assessment methodology used, global municipal wastewater generation is estimated to be between 330 and 400 billion m³ per year, with an estimated 40–45% being insufficiently treated prior to discharge [2,7].

Wastewater treatment has progressed through three main phases:

1. Organic load control (removal of BOD and TSS; see Section 2.1 for definitions).
2. Nutrient removal (nitrogen and phosphorus).
3. Micropollutant and pathogen control aligned with water reuse objectives.

The sector is shifting increasingly towards a circular resource recovery model that emphasises energy generation (biogas), nutrient recovery (e.g. struvite) and water reclamation.

This review provides a structured assessment of wastewater treatment technologies and potential development pathways. It synthesizes conventional biological treatment, AOPs, membrane technologies, and emerging systems within a systems-engineering framework, emphasizing both performance and practical feasibility. Emphasis is placed on energy demand, operational feasibility, regulatory drivers, and resource recovery integration. The objective is to clarify how existing and emerging technologies can be strategically combined to enable the transition toward energy-efficient, circular, and next-generation WWTPs.

A clear understanding of wastewater composition and quality parameters is fundamental for selecting appropriate treatment technologies.

2. Wastewater Pollutants, Characterization, and Types

Wastewater is a heterogeneous mixture of contaminants that can be categorised broadly as follows [1,5,11,13]:

- Physical contaminants: suspended solids, turbidity and settleable matter.
- Chemical contaminants include biodegradable and non-biodegradable organic compounds (e.g. detergents, phenols and pharmaceuticals), nutrients (e.g. nitrogen and phosphorus compounds), heavy metals, dissolved salts and other inorganic constituents.
- Biological contaminants include bacteria, viruses, protozoa and other pathogenic microorganisms.

Additionally, emerging contaminants, including endocrine-disrupting compounds, pharmaceutical residues, per- and polyfluoroalkyl substances (PFAS), microplastics, flame retardants and antibiotic resistance genes (ARGs) [11,12,14,30], have received increasing attention due to their persistence, potential for bioaccumulation and incomplete removal by conventional treatment processes.

Figure 1 includes a schematic of sources of wastewater contaminants, grouping domestic, industrial, and emerging contaminants, with color-coded categories for clarity.

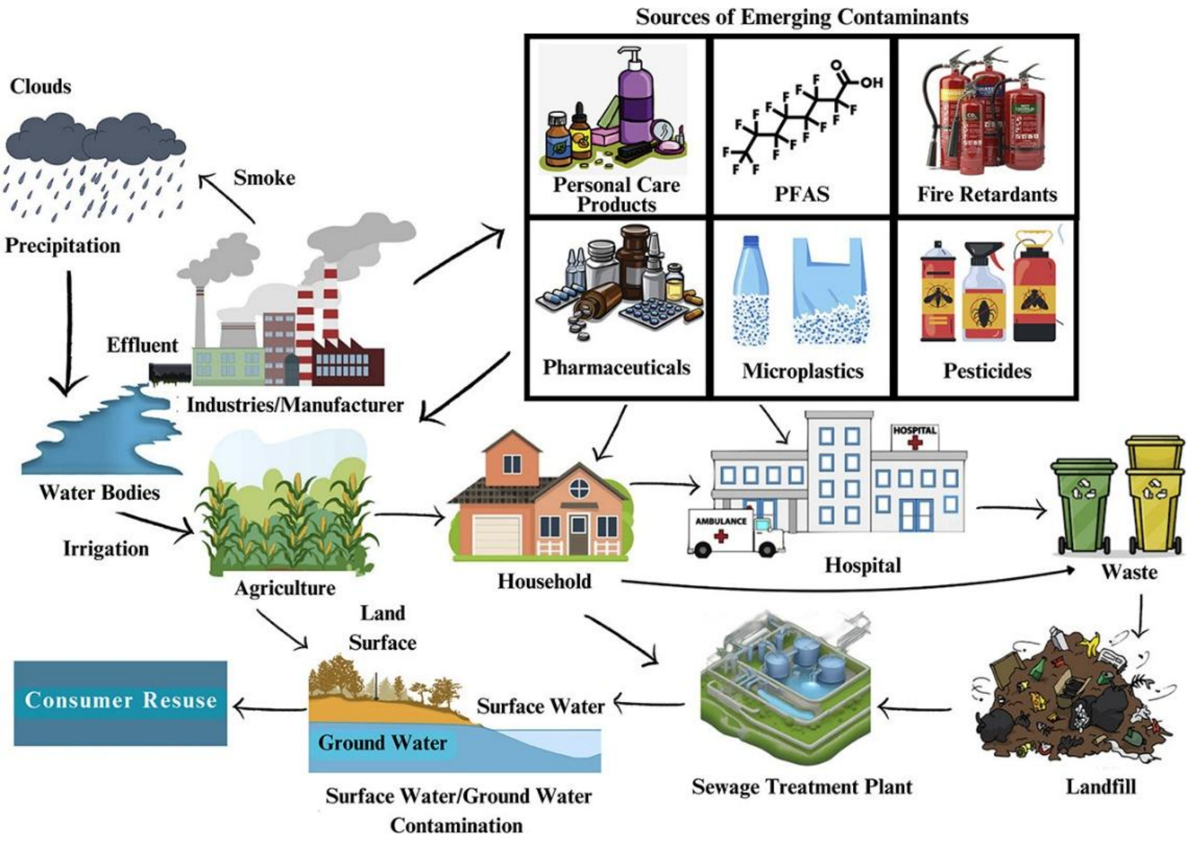


Figure 1: Sources of wastewater contaminants [1].

2.1 Key Wastewater Quality Parameters

Wastewater quality is typically characterized using the following core indicators:

- **Biochemical Oxygen Demand (BOD_5):** the amount of dissolved oxygen consumed by microorganisms over five days during aerobic degradation of biodegradable organic matter.
- **Chemical Oxygen Demand (COD):** the total quantity of oxygen required to chemically oxidize organic (and some inorganic) compounds, including biologically recalcitrant fractions.
- **Total Suspended Solids (TSS):** particulate matter affecting turbidity, sedimentation behavior, and downstream treatment performance.
- **Total Nitrogen (TN) and Total Phosphorus (TP):** nutrient species contributing to eutrophication in receiving waters.
- **Pathogens:** indicators of public health risk, typically expressed as log removal values.

BOD reflects biologically degradable organic matter, whereas COD represents total oxidizable material. The **BOD/COD ratio** serves as an indicator of biodegradability; values >0.4 generally suggest favorable biological treatability [1,5,13], while lower ratios indicate a higher fraction of recalcitrant compounds [5,16].

Table 1: Typical regulatory discharge limits in the EU and US for conventional and advanced wastewater treatment [1,31].

Parameter	Units	Conventional Secondary Effluent	Sensitive / Advanced Treatment	Notes / Footnotes
BOD_5	mg/L	≤ 25 (EU typical)	≤ 10	[1] EU standards; [2] Limits may vary by plant sensitivity
COD	mg/L	≤ 125 (EU typical)	≤ 50	[1] EU standards; [2] Dependent on influent composition
TSS	mg/L	≤ 35 (EU & US typical)	≤ 10	[1] US secondary standard; EU similar; [2] Sensitive waters may require stricter control
Total Nitrogen (TN)	mg/L	10–15	≤ 10 (often 5–8)	[2] Sensitive areas require enhanced nutrient removal
Total Phosphorus (TP)	mg/L	1–2	≤ 1 (often 0.3–0.5)	[2] EU sensitive areas; limits depend on discharge location
E. coli	CFU/100 mL	10^3–10^4	≤ 10–100	[3] Limits vary with **reuse class**; e.g., irrigation, recreational, or potable reuse

[1] EU: Typical standards for municipal secondary effluent according to UWWTD.
[2] Advanced/sensitive treatment depends on local regulations, water sensitivity, and plant capacity.
[3] Reuse class examples: Class A – unrestricted irrigation; Class B – restricted irrigation; Class C – recreational use; Class D – potable reuse (stringency increases A→D).

2.2 Wastewater Classification

Wastewater pollutants are best classified not only by their source, but also by the properties that control their treatability. These include phase and size (settleable solids, colloids, dissolved species), biodegradability, polarity and charge, volatility, oxidizability, toxicity, and persistence [5,13,16]. In practice, the core characterization set is first and foremost physical and chemical: flow, temperature, pH, conductivity or salinity, total suspended solids (TSS), turbidity, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4^+), nitrate (NO_3^-), total phosphorus (TP), orthophosphate (PO_4^{3-}), alkalinity, oils and grease, and, when relevant, specific toxicants such as sulfide, cyanide, phenols, solvents, dyes, and metals.

These parameters are not merely descriptive; they largely determine treatment process selection [5,16]. The treatment stages and processes will be described in detail in paragraph 3. High TSS, colloids, emulsified oil, and color typically indicate the need for physicochemical clarification. High biodegradable BOD/COD favors biological treatment. High dissolved salts, persistent micropollutants, or specific ions tend to push treatment toward adsorption or membrane processes. High turbidity, bromide, or dissolved organic carbon (DOC) can also strongly affect oxidation and membrane performance.

Wastewater treatment design is therefore fundamentally governed by the nature and properties of pollutants rather than by source alone. A rigorous and objective approach requires linking pollutant class, physicochemical properties, removal mechanisms, and process performance, including treatment efficiency, capital expenditure (CAPEX), operational expenditure (OPEX), and energy demand. In broad terms, wastewater contaminants are commonly categorized into domestic (municipal) wastewater, industrial wastewater, and emerging contaminants or micropollutants. The selection of treatment processes depends primarily on particle size (suspended, colloidal, or dissolved), biodegradability (often approximated through the BOD/COD ratio), solubility and polarity, toxicity and inhibition potential, oxidizability, and molecular size, especially when membrane treatment is considered.

The following subparagraphs provide a more detailed description of these wastewater classes, their pollutant characteristics, and the treatment processes most appropriate to their removal.

2.2.1 Domestic (Municipal) Wastewater

Domestic wastewater is typically dominated by biodegradable organic matter, suspended solids, nutrients, pathogens, surfactants, fats, oils, grease, and an increasing background of trace household chemicals and pharmaceuticals [1,5,16]. The main bulk indicators remain BOD_5, COD, TSS, TN, and TP, while pathogens and inhibitory substances must also be considered where water reuse or sludge quality is important. From a treatment-selection standpoint, this composition explains why conventional municipal treatment is generally built around primary clarification followed by aerobic biological treatment, often combined with nitrification-denitrification and phosphorus removal when nutrient limits apply. Coagulation/flocculation followed by sedimentation is usually useful mainly as a polishing or tertiary step for colloids, phosphorus, and turbidity, rather than as the principal barrier for dissolved biodegradable organics. Activated sludge and related aerobic systems [5,16] remain the default for municipal wastewater because they are robust and effective for bulk BOD/COD removal, although they are energy-intensive due to aeration. Anaerobic treatment is usually less favored for dilute domestic sewage than for stronger industrial streams [6], although it can be attractive in warm climates or for high-strength fractions because it reduces sludge production and recovers energy as biogas.

Accordingly, the recommended treatment train for domestic wastewater typically includes:

- primary sedimentation,
- aerobic biological treatment (for example, activated sludge),
- nutrient removal when required,
- tertiary polishing where needed.

Table 2: Typical Domestic Wastewater Characteristics

Parameter	Typical Range
pH	6.5 – 8.5
Conductivity	500 – 1500 µS/cm
TSS	150 – 400 mg/L
Turbidity	50 – 300 NTU
BOD_5	200 – 400 mg/L
COD	400 – 800 mg/L
TN	20 – 85 mg/L
TP	4 – 15 mg/L

2.2.2 Industrial Wastewater

Industrial wastewater is much more heterogeneous, so source-specific characterization is essential before choosing treatment and must therefore requires case-specific treatment design.

Petrochemical and refinery wastewater

This industrial wastewater typically contains oils and grease (50 – 500 mg/L), hydrocarbons, aromatics such as benzene/toluene/xylene, sulfides, ammonia, phenols, and sometimes metals [1,15]; here the process logic is typically gravity separation or dissolved-air flotation for free/emulsified oil, then biological treatment for biodegradable COD (500 – 5,000 mg/L) and ammonium/sulfide, with AOPs, carbon, or membranes reserved for refractory aromatics and reuse polishing. Its Treatment selection depends on the dominant pollutant type as shown in Table 3:

Table 3: Industrial Treatment Matching

Pollutant Type	Best Treatment
Oils	Separation / flotation
Biodegradable COD	Biological
Color/dyes	Coagulation / flocculation
Metals	Precipitation
Salts	RO
Toxic organics	AOP / activated carbon

Agro-food Industry Wastewater

Food and agro-industrial effluents are usually rich in biodegradable COD and BOD, TSS, fats, nitrogen, and phosphorus. These are among the clearest cases for anaerobic treatment [6,16] followed by aerobic polishing, because the wastewater strength is often high enough to justify methane recovery and because biological treatment is generally the lowest-OPEX route for biodegradable organics. Because of its high biodegradability, anaerobic digestion is often preferred, as it enables energy recovery through biogas production and can then be followed by aerobic polishing to improve final effluent quality. Depending on the process line, pretreatment may also be required to remove coarse solids, fats, oils, and grease before anaerobic conversion.

Table 4: Typical agro-food wastewater characteristics

Parameter	Range
COD	2,000 – 20,000 mg/L
BOD_5	1,000 – 10,000 mg/L
BOD/COD	0.5 – 0.8
TSS	500 – 5,000 mg/L

Textile Wastewater

Textile effluents are characterized by color, dyes, auxiliary chemicals, salts, surfactants, and, in some cases, metal-complex dyes containing Pb, Cr, Cd, or Cu. Their composition is often highly variable, and both color and salinity can be important design constraints. Because color and colloids respond well to charge neutralization, coagulation/flocculation is often one of the first cost-effective treatment steps [4,12]. Biological treatment can be applied when a sufficient biodegradable fraction exists, but it is often insufficient on its own for full color removal or salt reduction. NF/RO or adsorption is generally selected when salt removal, color polishing, or water reuse targets are stringent. Textile wastewater is therefore a typical case in which combined treatment trains are favored, especially when the goal is not only compliance but also reuse.

Pharmaceutical Wastewater

Pharmaceutical manufacturing wastewater is one of the clearest cases where bulk biological treatment alone is often insufficient. Such wastewater may contain poorly biodegradable or bioactive compounds such as antibiotics, anti-inflammatory compounds, steroids, hormones, antidepressants, and spent solvents [11,12,14]. These matrices may also inhibit biomass depending on concentration and composition. As a result, these streams often require a combined treatment train, for example equalization followed by biological treatment, then activated carbon, ozonation or other AOPs, and/or NF/RO depending on the discharge target or reuse objective. Pharmaceutical wastewater is therefore a representative example of a stream in which both biodegradability and toxicity must be evaluated before selecting the treatment sequence.

Metal and Mining Wastewater

A separate class within industrial wastewater is inorganic and metal-bearing effluent, including mining, metal finishing, electroplating, semiconductor manufacturing, and certain chemical-process wastewaters. These streams may contain dissolved heavy metals such as Cr, Ni, Cu, Zn, Cd, Pb, Fe, or Mn [15], together with acidity or alkalinity, high conductivity, cyanide (CN^-), fluoride (F^-), sulfate (SO_4^{2-}), and sometimes complexing agents that keep metals soluble. Typical pH values may range from about 2 to 10, while dissolved metals may vary from about 1 to 500 mg/L depending on the source.

For these wastewaters, biological treatment is generally not the primary barrier, because toxicity and poor biodegradability are often limiting. The preferred front-end usually consists of chemical precipitation, pH adjustment, coagulation/flocculation, and sedimentation for metals and colloids, optionally followed by filtration, activated carbon, ion exchange, NF, or RO when very low residual concentrations or water reuse are required. This is a good example of a broader rule: when the dominant pollution is dissolved inorganic or ionic rather than biodegradable organic, separation processes usually outperform biological ones.

Emerging Contaminants

Emerging contaminants are a distinct category because they are often present at low concentrations yet are persistent, mobile, biologically active, or poorly removed by conventional treatment. Major groups include pharmaceuticals, personal-care products, surfactants and detergent residues, natural and synthetic hormones, industrial additives, per- and polyfluoroalkyl substances (PFAS), and microplastics. The U.S. Environmental Protection Agency (EPA), in its early POTW work, explicitly grouped contaminants of emerging concern around pharmaceuticals, detergents, and natural and synthetic hormones, while the OECD has noted that conventional wastewater treatment plants are not designed to remove pharmaceuticals reliably [11,12,30,31]. This distinction is important in practice: a stream can appear “clean” in terms of BOD_5, COD, and TSS and still fail with respect to micropollutant removal.

For that reason, emerging contaminants are usually selected and treated according to molecular properties such as hydrophobicity, charge, molecular size, and oxidizability, rather than according to bulk oxygen demand alone. Hydrophobic and adsorbable compounds may respond well to activated carbon; oxidizable compounds may be degraded by ozonation or AOPs; and small, persistent, and mobile compounds may require NF or RO.

Table 5: Main processes for micropollutant removal

Process	Efficiency	Limitation
Activated carbon [12]	70–95%	Saturation / exhaustion
Ozonation [10,22]	60–95%	By-product formation
AOP [21]	>90%	High cost and energy demand
NF [4,19]	>90%	Partial removal depending on compound
RO [4,19]	>95–99%	Concentrate management

3. Conventional Treatment Stages and Processes

Wastewater treatment is usually organised into a series of conventional stages, which are designed to progressively remove pollutants and protect human health and the environment [1,5]. As shown in Figure 2, the treatment process generally follows a logical sequence: **preliminary** treatment to remove coarse debris and protect equipment; primary sedimentation to settle solids and reduce the organic load; **secondary** biological treatment to degrade dissolved organics and remove nutrients; and **tertiary/quaternary** polishing processes to eliminate residual solids, pathogens, nutrients and micropollutants. The purpose of each stage becomes more specific and the technical complexity and energy demand increase as water quality targets become more stringent. This staged approach allows for the integration of advanced treatment technologies, such as membrane filtration, advanced oxidation processes or hybrid systems, in order to meet regulatory standards and reuse objectives.

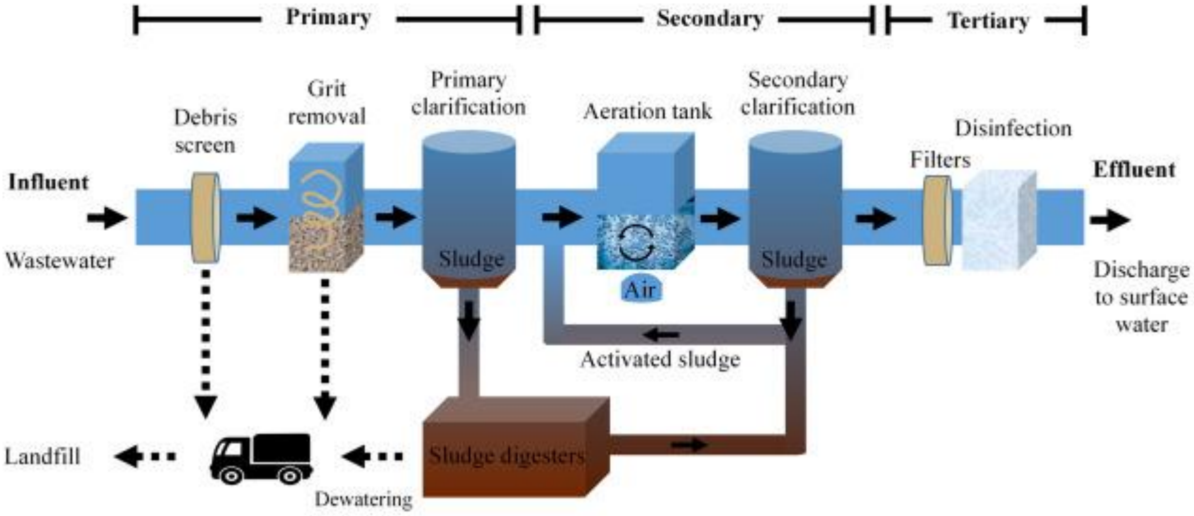


Figure 2: Main conventional stages of wastewater treatment process [3].

3.1 Preliminary Treatment (Screening and Grit Removal)

Purpose: Protect downstream equipment by removing coarse debris, grit, and large solids [1].

- **Screening:** Removes coarse solids (>6 mm) such as plastics, rags, and sticks.
- **Grit Removal:** Removes inorganic particles (sand, gravel) to prevent abrasion and sedimentation in pumps and clarifiers.
- **Hydraulic Retention Time (HRT):** ~30–60 s.
- **Energy Demand:** Minimal compared to biological processes.

Note: Preliminary treatment does not significantly reduce dissolved organics or nutrients; it is strictly protective.

3.2 Primary Sedimentation

Purpose: Remove contaminants which are particulate, colloidal, strongly colored, phosphorus-rich, or present as emulsified oil [1,5].

- **Mechanism:** Gravity settling in primary clarifiers.
- **Removal Efficiency:**
    - TSS: 50–70%
    - BOD: 25–40%
- **HRT:** 1.5–2.5 h
- **Primary Sludge Production:** ~0.02–0.04 kg TSS/m^3 treated.
- **Energy Demand:** Low (mainly pumping).
- **Limitations:**
    - Dissolved organics largely remain.
    - Sludge requires stabilization.

Application Note: Some coarse chemical treatments (e.g., coagulation/flocculation) may precede sedimentation in industrial wastewater.

3.3 Secondary Biological Treatment

Purpose: Degrade dissolved organics and remove nutrients using microorganisms [5,16].

3.3.1 Activated Sludge Process (ASP)

- **Mechanism:** Aerobic heterotrophic metabolism converts organics into CO_2, H_2O, and biomass.
- **Typical Operating Parameters:**
    - Mixed Liquor Suspended Solids (MLSS): 2,000–4,000 mg/L

    (Concentration of suspended biomass in the aeration tank, indicating microbial inventory).
  - Sludge Retention Time (SRT): 5–20 days

    (Average time biomass remains in the system; controls microbial community composition and process stability).
  - Hydraulic Retention Time (HRT): 6–8 h

    (Average time wastewater remains in the reactor; determines contact time between microorganisms and substrate).
  - Oxygen demand: ~1.2–1.5 kg O_2/kg BOD removed
- **Removal Efficiency:**
  - BOD: >95%
  - TSS: >95%
- **Energy Consumption:** 0.3–0.6 kWh/m^3; aeration is 50–60% of total plant energy [2,17].

3.3.2 Biological Nutrient Removal (BNR)

- **Mechanism:** Sequential aerobic/anoxic zones for nitrification–denitrification; enhanced biological phosphorus removal (EBPR) for phosphorus [5,16].
- **Effluent Nitrogen:** <10 mg/L achievable in optimized systems.
- **Energy Consideration:** Aeration-intensive; requires careful control of oxygen and carbon sources.

3.3.3 Anammox

- **Mechanism:** Anaerobic ammonium oxidation [18]: $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$
- **Advantages:**
  - ~60% lower oxygen demand
  - No external carbon required
- **Challenges:** Slow growth (doubling time 10–12 days), oxygen sensitivity
- **Applications:** Increasingly used in sidestream treatment (high ammonium concentration streams from sludge digestion).

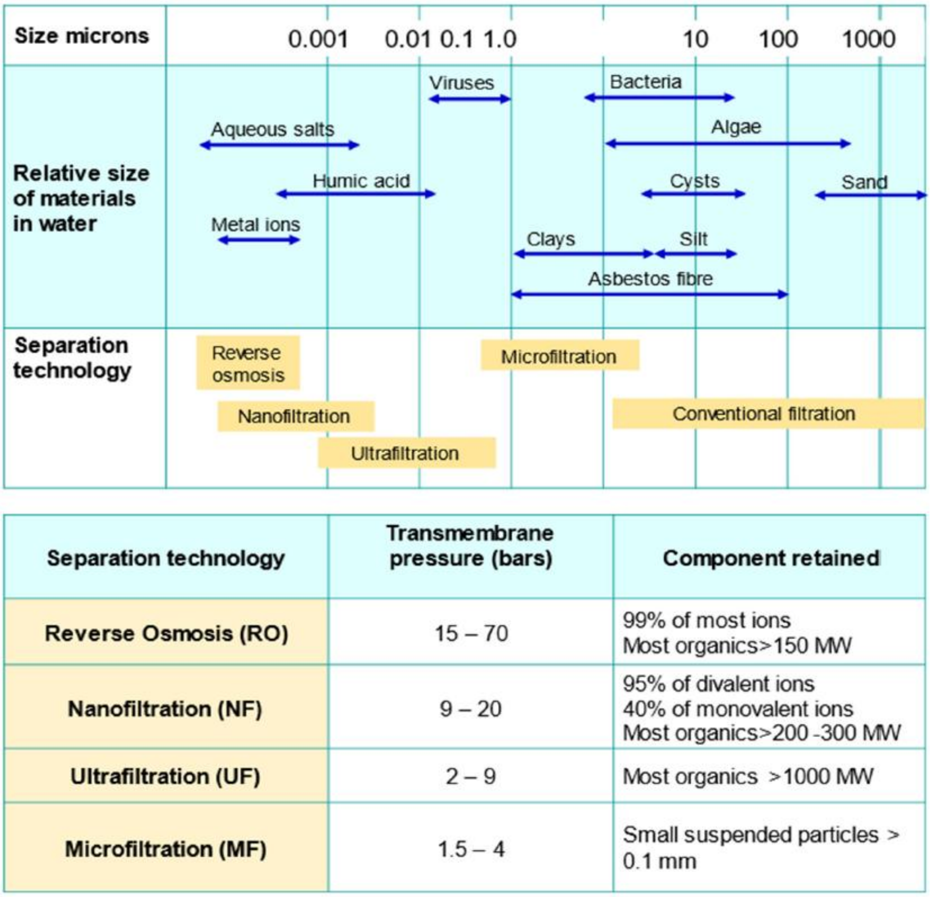
Practical Note: Secondary biological treatment primarily addresses BOD, TSS, and nutrients; it does **not remove micropollutants or pathogens** to regulatory discharge standards.

3.4 Tertiary and Quaternary Treatment (Polishing Stage)

Purpose: Polishing stage to remove residual suspended solids, pathogens, nutrients, and micropollutants unmet by secondary treatment.

3.4.1 Membrane Technologies (Microfiltration (MF) / Ultrafiltration (UF) / Nanofiltration (NF) / Reverse Osmosis (RO))

- **Mechanism:** Physical separation across pressure-driven membranes, with decreasing pore size and increasing selectivity from MF to RO [4,9,19].
- **Applications:**
    - MF/UF: remove remaining TSS, bacteria, and protozoa.
    - NF/RO: remove salts, micropollutants, and some organic contaminants.
- **Energy Demand:** 0.8–3 kWh/m³ depending on membrane type.
- **Limitations:** Fouling, high-pressure requirements, concentrate disposal.



Separation technology	Transmembrane pressure (bars)	Component retained
Reverse Osmosis (RO)	15 – 70	99% of most ions Most organics>150 MW
Nanofiltration (NF)	9 – 20	95% of divalent ions 40% of monovalent ions Most organics>200 -300 MW
Ultrafiltration (UF)	2 – 9	Most organics >1000 MW
Microfiltration (MF)	1.5 – 4	Small suspended particles > 0.1 mm

Figure 3: Size-based separation ranges and operating pressures of membrane filtration processes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), in relation to typical water contaminants. Adapted from *A Review on the Use of Membrane Technology Systems in Developing Countries* [4].

To further contextualize the separation capabilities and operational requirements of pressure-driven membrane systems, Figure 3 provides a comparative overview of membrane processes in relation to particle size ranges and corresponding transmembrane pressures. The figure illustrates the progressive selectivity from microfiltration (MF) to reverse osmosis (RO), highlighting the ability of membranes to target specific contaminant classes, from suspended solids and microorganisms to dissolved ions and low-molecular-weight organic compounds. In particular, reverse osmosis demonstrates the highest separation efficiency, capable of removing up to 99% of dissolved ions, albeit at significantly higher operating pressures (15–70 bar). In contrast, microfiltration and ultrafiltration operate at lower pressures and are primarily effective for particulate matter and high-molecular-weight organics. This classification underscores the trade-off between selectivity and energy demand, which is a critical consideration in the design of advanced wastewater treatment systems.

3.4.2 Sand Filtration

- **Mechanism:** Physical removal of residual TSS.
- **Use Case:** Often combined with chemical coagulation for enhanced polishing.

3.4.3 Activated Carbon Adsorption

- **Mechanism:** Adsorption of dissolved organics and micropollutants via physical (van der Waals) and chemical interactions [12].
- **Limitations:** Regeneration costs and competitive adsorption; efficiency depends on water chemistry.

3.4.4 Chlorine-Based Disinfection

Chlorine-based disinfection remains one of the most widely applied tertiary treatment steps in municipal wastewater treatment plants (WWTPs), particularly where effluent discharge or reuse standards require pathogen inactivation. Chlorine is typically dosed as chlorine gas (Cl_2), sodium hypochlorite (NaOCl), or calcium hypochlorite ($Ca(OCl)_2$) [1,13]. In water, these compounds generate hypochlorous acid (HOCl), the principal active disinfectant:

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

Hypochlorous acid partially dissociates depending on pH:

$$HOCl \rightleftharpoons H^+ + OCl^-$$

Disinfection efficiency is strongly pH-dependent; HOCl predominates at $pH < 7.5$ and exhibits significantly higher microbial inactivation kinetics than the hypochlorite ion (OCl^-). The mechanism involves oxidative damage to cell membranes, proteins, and nucleic acids, resulting in rapid inactivation of bacteria and viruses under appropriate contact time (CT) conditions.

In some applications, chlorine reacts with ammonia to form monochloramine (NH_2Cl), providing a more stable but weaker disinfectant residual. Beyond pathogen control, chlorine also oxidizes reduced inorganic species (e.g., Fe^{2+}, Mn^{2+}, H_2S) and contributes to biofilm control in distribution systems.

Limitations include the formation of disinfection by-products (DBPs) in the presence of natural organic matter and limited effectiveness against certain protozoa [12]. Dechlorination is often required prior to discharge to prevent ecotoxicological impacts. While chlorine-based disinfection is energy-efficient compared to UV or advanced oxidation processes, it primarily targets pathogens and does not effectively remove persistent micropollutants.

From a process-engineering perspective, conventional treatment systems are optimized for bulk pollutant removal rather than for the transformation of persistent dissolved contaminants. As a result, additional treatment barriers are required when the objective extends beyond BOD, TSS, and nutrient compliance toward micropollutant removal and water reuse. This need has led to the integration of advanced oxidation processes and other tertiary technologies, discussed in the following section.

4. Direct Oxidation and Advanced Oxidation Processes

Direct oxidation and radical oxidation, including ozone, O_3/H_2O_2, UV/H_2O_2, and related Advanced Oxidation Processes (AOPs) [21], are most appropriate for refractory dissolved organics, color bodies, phenolics, many pharmaceuticals, and toxicity reduction when biological treatment is incomplete or impossible [11,22]. Their mechanism is not primarily solids removal, but chemical transformation, often through highly reactive hydroxyl radicals ($\bullet OH$, $E^\circ = 2.8$ V).

These processes therefore perform best after adequate solids removal and generally after secondary treatment, when turbidity is lower and radical scavenging by background organic matter is reduced. Reviews of UV-based AOPs report that such systems can remove pharmaceuticals and dyes very effectively, often above 90% in studied cases, but they also emphasize higher operating costs, by-product risks, and declining efficiency in turbid waters. For ozonation specifically, bromate formation from bromide is a recognized control issue.

In practice, AOPs are typically justified when target pollutants are dissolved and recalcitrant, the wastewater is not excessively rich in solids, and the treatment objective is advanced discharge or reuse rather than simple BOD compliance. AOPs, UV-based processes, and hydrodynamic cavitation are primarily applied as **tertiary or quaternary treatment**, following conventional secondary biological treatment, to achieve high effluent quality.

In comparison with other advanced treatment options, AOPs differ fundamentally in their removal mechanism. While adsorption processes such as activated carbon transfer contaminants from the aqueous phase to a solid phase, and membrane processes such as nanofiltration (NF) and reverse osmosis (RO) physically separate pollutants based on size and charge, AOPs aim to chemically transform or mineralize target compounds [4,11,21]. As a result, AOPs are particularly advantageous for degrading oxidizable micropollutants, whereas adsorption and membrane processes are often preferred when complete removal without transformation, or retention of a broad spectrum of contaminants including non-oxidizable species, is required.

4.1 Ozonation (O_3)

- **Mechanism [10,22]:** $O_3 \rightarrow O_2 + \bullet OH$
- **Applications:** Effective for pharmaceuticals, endocrine-disrupting chemicals, and other trace organics.
- **Removal Efficiency:** 70–99% for micropollutants.
- **Energy Demand:** 10–20 kWh/kg O_3.
- **Limitations/Risks:** Formation of bromate in bromide-containing waters.

- **Implementation:** Typically applied before filtration or activated carbon polishing in the tertiary stage.

4.2 UV/H_2O_2

- **Mechanism [21]:** $H_2O_2 + UV \rightarrow 2{\bullet}OH$
- **Applications:** High degradation efficiency for trace organics and pathogens.
- **Requirements:** Controlled UV transmittance, clean water prior to treatment to avoid shading effects.
- **Energy Demand:** High; careful design needed for cost-effectiveness.
- **Implementation:** Post-secondary treatment; can also complement ozonation in hybrid AOPs.

4.3 Fenton and Photo-Fenton Processes

- **Mechanism [21]:** $Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {\bullet}OH + OH^-$
- **Applications:** Effective for industrial effluents and concentrated streams with refractory organics.
- **Optimal Conditions:** Acidic pH (~3).
- **Limitations:** Sludge generation, chemical cost, and limited feasibility for full-scale municipal flows.
- **Implementation:** Tertiary stage; usually in pilot or specialized industrial applications.

Zinc peroxide (ZnO_2) serves as a solid, slow-release source of hydrogen peroxide, enabling localized Fenton-type hydroxyl radical generation in the presence of ferrous iron. Compared with conventional Fenton processes, ZnO_2 exhibits slower kinetics and lower peak oxidation capacity, which can be advantageous for controlled oxidation but limits large-scale municipal applications due to potential Zn^{2+} accumulation and limited operational validation.

4.4 Electrochemical Oxidation

- **Mechanism:** Direct and indirect oxidation at the anode surface [23,24].
- **Applications:** High mineralization efficiency for high-strength industrial wastewater.
- **Limitations:** High electrode and energy costs; rarely applied at full-scale municipal WWTPs.
- **Implementation:** Typically tertiary, suited for concentrated industrial streams.

4.5 Hydrodynamic Cavitation (HC)

- **Mechanism:** Bubble collapse generates localized extreme temperatures (>5000 K) and pressures (>100 atm), producing hydroxyl radicals [25,26].
- **Advantages:**
    - Rapid degradation of complex organics

    - Can synergize with ozone or H_2O_2 for hybrid AOPs
- **Challenges:** Reactor design complexity, energy efficiency at high scale
- **Implementation:** Tertiary/hybrid stage; not effective in primary or secondary treatment due to low pollutant concentration.

4.6 Placement of AOPs, UV, and Cavitation in Treatment Trains

Advanced oxidation processes (AOPs), ultraviolet (UV) systems, and hydrodynamic cavitation are typically implemented in the tertiary or polishing stage of wastewater treatment trains. Their placement depends on influent characteristics, target contaminants, regulatory requirements, and overall process integration. Table 6 summarizes the typical positioning, target contaminants, and key practical considerations associated with these technologies.

Taken together, the most defensible treatment-selection logic is property-based rather than source-based. Coagulation/flocculation followed by sedimentation should be selected when the main problem is solids, colloids, emulsions, phosphorus, or color. Aerobic biological treatment should be selected when the main load consists of biodegradable BOD/COD and nutrients. Anaerobic biological treatment becomes attractive when COD is sufficiently high to justify energy recovery and sludge minimization. AOPs are particularly suited to dissolved organics that are refractory, toxic, or poorly biodegradable, especially when the matrix has already been clarified. MF/UF are best used as pretreatment and as solids/pathogen barriers, whereas NF/RO are more appropriate when salts, small dissolved organics, PFAS, or high-end reuse criteria dominate the design basis. Activated carbon is especially useful when the target is a broad spectrum of dissolved organic micropollutants and when concentrate management associated with RO is undesirable.

In practice, the most successful plants are not single-process systems but staged treatment trains in which low-cost bulk removal is applied first and high-cost polishing is reserved for those contaminants that truly require it.

Table 6: Typical placement of selected advanced treatment technologies within wastewater treatment trains, including target contaminants and operational considerations.

Technology	Stage	Target Contaminants	Practical Notes
UV / UV/H_2O_2	Tertiary	Pathogens, trace organics, endocrine disruptors	After filtration; high energy demand but highly effective for disinfection and micropollutant removal
Ozonation (AOP)	Tertiary	Pharmaceuticals, micropollutants, endocrine disruptors	Can precede sand/activated carbon polishing; generates some oxidation byproducts
Hydrodynamic Cavitation	Tertiary / hybrid	Complex organics, pharmaceuticals	Often combined with AOPs for enhanced radical formation; unsuitable for low-concentration influents
Fenton / Photo-Fenton	Tertiary	Trace organics in concentrated streams	Requires pH adjustment; sludge handling required; limited municipal application

4.7 Comparative Assessment of Chemical Oxidants

Beyond individual process descriptions, a systematic comparison of chemical oxidants is necessary to support technology selection in advanced wastewater treatment design. Oxidants differ substantially in oxidation strength, selectivity, reaction kinetics, operational complexity, cost structure, and environmental implications.

Ozone and hydroxyl-radical–based systems (e.g., Fenton or UV/H_2O_2) provide high oxidation potentials suitable for micropollutant degradation and recalcitrant organic compounds. However, these technologies are energy- or chemical-intensive and may introduce secondary effects such as bromate formation (ozonation) or iron-sludge generation (Fenton).

Chlorine-based oxidants remain the dominant chemical disinfectants in municipal practice due to their cost-effectiveness, operational simplicity, and reliable pathogen inactivation performance. Their oxidative capacity toward persistent micropollutants, however, is limited, and disinfection by-product (DBP) formation must be carefully controlled.

Zinc peroxide represents a controlled-release oxidant with slower kinetics and more specialized applications, such as localized oxidation or sludge conditioning, but lacks broad validation at large municipal scales.

A structured technical comparison of selected oxidants—including ozone, hydrogen peroxide, zinc peroxide, Fenton systems, and chlorine-based compounds—is provided in **Annex A** to support decision-oriented evaluation.

5. Emerging Technologies for Wastewater Treatment

Emerging technologies aim to address **recalcitrant pollutants, energy efficiency, and resource recovery** beyond conventional and tertiary treatment. Most are currently at pilot or demonstration scale and face challenges in scalability, cost, and operational complexity.

5.1 Photocatalysis (TiO_2)

- **Principle:** Photocatalysis uses semiconductors (commonly titanium dioxide, TiO_2) activated by UV light to generate electron-hole pairs, which produce hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$) that oxidize organic contaminants [27].
- **Applications:** Effective for trace organics, pharmaceuticals, and endocrine-disrupting compounds in low-TSS water.
- **Advantages:** Chemical-free process, high selectivity for micropollutants.
- **Limitations:**
  - Low quantum efficiency due to rapid electron-hole recombination
  - UV-light penetration limited in turbid water
  - Requires post-treatment separation of catalyst if suspended
- **Implementation:** Tertiary stage; typically, after secondary treatment and filtration.

5.2 Microbial Fuel Cells (MFCs)

- **Principle:** MFCs harness electroactive microorganisms to degrade organic matter while transferring electrons to an anode, generating electricity [28,6].

- **Applications:** Wastewater treatment with simultaneous energy recovery. Potentially useful for low-strength domestic or industrial wastewater streams.
- **Performance:** Power density typically 1–2 W/m^2.
- **Limitations:**
  - Low power output relative to treatment scale
  - Electrodes and membranes increase capital cost
  - Not yet economically viable for full-scale municipal applications
- **Implementation:** Emerging decentralized or pilot-scale energy-positive wastewater systems.

5.3 Forward Osmosis (FO)

- **Principle:** FO uses osmotic pressure gradients to draw water across a semi-permeable membrane from feed water to a concentrated draw solution, leaving contaminants behind [19,20].
- **Applications:** Water concentration, nutrient recovery, pre-treatment for desalination or AOPs.
- **Advantages:** Low fouling tendency, lower hydraulic pressure than reverse osmosis.
- **Limitations:**
  - Regeneration of the draw solution is energy-intensive
  - Requires careful selection of draw solute for downstream usability
- **Implementation:** Tertiary or advanced treatment stage, especially for water reuse and resource recovery.

5.4 Cold Plasma

- **Principle:** Cold plasma (non-thermal plasma) generates reactive species (•OH, O_3, H_2O_2, reactive nitrogen species) in water through electrical discharges without chemical addition [29].
- **Applications:** Effective for degrading micropollutants, pharmaceuticals, dyes, and pathogens in water.
- **Advantages:** Rapid oxidation, chemical-free, flexible reactor design.
- **Limitations:**
  - High capital and operational costs
  - Energy demand can be high, depending on scale
- **Implementation:** Tertiary/quaternary stage; mostly pilot-scale for industrial or specialized municipal applications.

6. Regulatory Drivers in Wastewater Treatment

Regulatory frameworks are a major driver for wastewater treatment technology selection, pollutant removal targets, and investment in advanced processes. They define effluent standards, pollutant monitoring requirements, and increasingly, sustainability and resource recovery goals.

6.1 European Union

- **Framework:** The Urban Wastewater Treatment Directive (UWWTD, 91/271/EEC) establishes minimum requirements for collection, treatment, and discharge of urban wastewater and certain industrial effluents [1].
- **Recent Revisions (Effective 2025):**
    - Expanded nutrient (nitrogen and phosphorus) removal, especially in sensitive areas
    - Mandatory tertiary/quaternary treatment for selected micropollutants
    - Energy neutrality objectives for wastewater treatment plants
    - Extended producer responsibility for the cost of micropollutant removal
- **Emerging Enforcement:** Monitoring requirements now include microplastics and persistent organic pollutants, which incentivize adoption of advanced oxidation, membrane separation, and hybrid treatment technologies.
- **Practical Impact:** EU WWTPs are increasingly shifting from conventional biological treatment to integrated, energy-optimized, and multi-barrier systems capable of meeting stricter effluent quality and environmental sustainability standards.

For example, under the revised Urban Wastewater Treatment Directive, large wastewater treatment plants serving populations above 100,000 population equivalent are expected to implement quaternary treatment targeting selected micropollutants, with removal targets typically in the range of 70–80% for defined indicator substances. In addition, total phosphorus limits in sensitive areas may be reduced to 0.3–0.5 mg/L, while total nitrogen concentrations are often required to fall below 5–10 mg/L, depending on receiving water sensitivity. These increasingly stringent thresholds are expected to drive the adoption of advanced oxidation processes, membrane filtration, and adsorption technologies.

6.2 United States

- **Framework:** The Clean Water Act (CWA) establishes the National Pollutant Discharge Elimination System (NPDES), which sets effluent limits and requires the use of best available technology (BAT) for point-source discharges [31].
- **Emerging Issues:** Regulatory thresholds for PFAS (per- and polyfluoroalkyl substances) are under development, reflecting increasing concern about persistent and bioaccumulative contaminants.
- **Practical Impact:** Stricter discharge limits drive implementation of advanced treatment technologies (e.g., membrane filtration, advanced oxidation, and tertiary nutrient removal) in municipal and industrial facilities, particularly for micropollutant and recalcitrant compound removal.

In the United States, tightening regulatory focus on PFAS has led to proposed drinking water limits in the low ng/L range (e.g., 4 ng/L for PFOA and PFOS), which are several orders of magnitude lower than conventional wastewater discharge parameters. Although effluent limits for PFAS are still evolving, these thresholds are already influencing treatment design, favoring high-rejection technologies such as reverse osmosis and activated carbon adsorption. Similarly, nutrient discharge limits in sensitive watersheds (e.g., Chesapeake Bay) often require total nitrogen concentrations below 3–5 mg/L, necessitating advanced biological nutrient removal and process optimization.

7. Challenges and Perspectives

Despite significant technological progress, wastewater treatment faces persistent systemic challenges that affect both performance and practical implementation. These challenges influence plant design, operation, energy consumption, and regulatory compliance.

7.1 Removal of Emerging Contaminants

- **Issue:** Conventional chlorination is generally insufficient for the degradation of persistent micropollutants such as PFAS and many pharmaceuticals [30,31], reinforcing the need for AOPs, adsorption, or membrane-based polishing in advanced WWTP configurations [11,12,30].
- **Implication:** Effective removal frequently requires advanced tertiary/quaternary processes, including advanced oxidation processes (AOPs), membrane filtration, and hybrid systems.
- **Practical Consideration:** The choice of technology must balance removal efficiency, operational complexity, and energy demand.

7.2 Energy Demand and Operational Cost

The energy demand of a wastewater treatment plant (WWTP) depends on several key factors, including its geographical location, plant capacity (expressed as population equivalent or organic/hydraulic load), applied treatment technology, aeration system configuration, required effluent standards, plant age, and operational management efficiency.

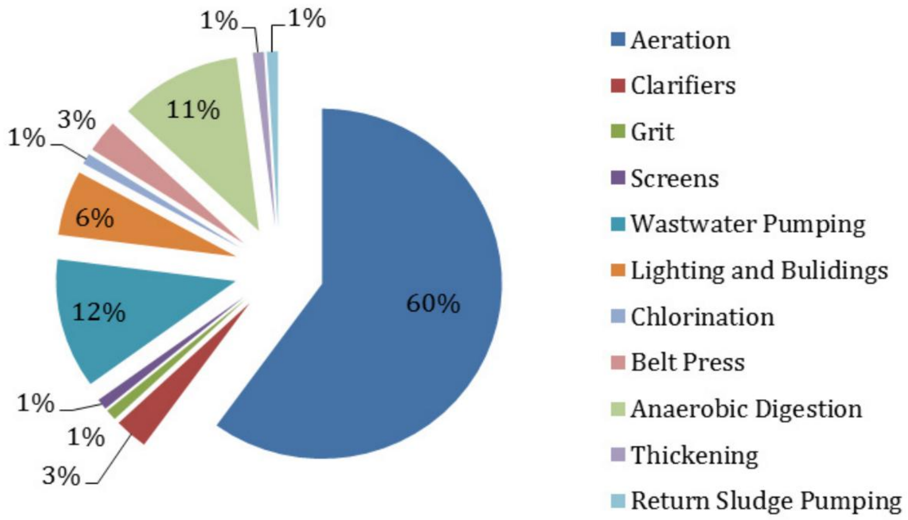


Figure 4: Energy distribution in a conventional activated sludge system [2].

A conventional municipal WWTP typically comprises primary, secondary, and advanced treatment stages. Among these, the aeration process in the secondary (biological) treatment stage represents the largest share of total energy consumption. Wastewater pumping is generally the second most energy-intensive operation. This distribution is illustrated in Figure 4 [2].

Benchmarking energy consumption across WWTPs in different countries is both relevant and informative, as it provides insight into performance gaps, technological differences, and improvement potential. Table 7 presents national-level data on energy intensity and total energy consumption in WWTPs across various countries.

From an operational and sustainability perspective, the following aspects are particularly relevant:

- **Issue:** Advanced treatment processes such as UV irradiation, reverse osmosis (RO), and advanced oxidation processes (AOPs) substantially increase specific energy consumption, operational expenditures (OPEX), and the overall carbon footprint of WWTPs.
- **Opportunity:** The integration of resource recovery strategies—including anaerobic digestion with biogas production, heat recovery, and nutrient recovery (e.g., struvite precipitation)—offers significant potential to offset energy demand, reduce life-cycle impacts, and enhance economic performance.
- **Practical Consideration:** Achieving sustainable and cost-effective WWTP operation requires energy-efficient plant design, optimized aeration control strategies (e.g., real-time DO control, fine-bubble diffusers), minimization of hydraulic losses, and systematic integration of energy recovery loops.

Table 7: Energy intensity proportion and energy consumption in WWTPs at national level in different countries [2].

Regions/Countries	Energy intensity (kWh/m^3)	Proportion of energy consumption national level (%)
USA	0.52	0.60
China	0.31	0.25
Germany	0.40-0.43	0.70
South Africa	0.079-0.41	-
Japan	0.304	-
Korea	0.243	0.5
Sweden	0.42	1

7.3 Scale-up and Technology Deployment

- **Issue:** Many innovative methods (e.g., acoustic cavitation, cold plasma, microbial fuel cells) demonstrate promising laboratory or pilot-scale performance but face challenges in full-scale industrial implementation.
- **Constraints:** Technical complexity, energy requirements, hydraulic scalability, and regulatory validation often limit widespread adoption.
- **Practical Consideration:** Pilot-to-full-scale studies and cost-benefit analyses are critical to identify viable pathways for industrial deployment.

7.4 Digitalization and Process Control

- **Opportunity:** IoT, AI-based predictive control, and digital twin modeling enable real-time optimization of aeration, chemical dosing, and energy use.

- **Impact:** Digital tools can enhance effluent quality, reduce energy consumption, and improve operational reliability, particularly for advanced treatment systems handling micropollutants.
- **Future Perspective:** Integration of smart monitoring and adaptive control is expected to become a standard component of next-generation, energy-optimized WWTPs.

8. Integration Strategies for Next-Generation WWTPs

Future wastewater treatment plants will not rely on single breakthrough technologies but on the strategic integration of biological, physicochemical, and digital systems. The transition from conventional pollution control facilities to resource-recovery-driven treatment hubs requires coordinated process design across multiple functional layers.

8.1 Multi-Barrier Treatment Architecture

Next-generation WWTPs increasingly adopt a multi-barrier configuration in which [7,11]:

- Biological treatment removes bulk organics and nutrients.
- Membrane systems (e.g., MBR, UF/NF) enhance solids and pathogen removal.
- Advanced oxidation processes (AOPs) or adsorption steps address micropollutants.
- Final polishing ensures compliance with reuse or discharge standards.

This layered approach improves robustness, reduces single-process dependency, and enhances effluent reliability under variable loading conditions.

8.2 Hybrid Biological–Advanced Treatment Systems

Integration strategies increasingly combine [11,21]:

- Biological nutrient removal with ozonation or UV/H_2O_2 for micropollutant degradation.
- Hydrodynamic cavitation coupled with oxidants for enhanced radical generation.
- Membrane bioreactors (MBRs) linked to activated carbon adsorption.

Such hybrid systems allow partial oxidation to increase biodegradability upstream or polishing downstream to achieve trace contaminant removal. The key challenge lies in balancing energy demand and operational complexity against incremental performance gains.

8.3 Energy-Optimized Design and Resource Recovery

Energy integration is central to next-generation plants. Strategies include [6,7]:

- Anaerobic digestion for biogas production.
- Heat recovery from effluent streams.
- Nutrient recovery (e.g., struvite precipitation).
- Sidestream treatment with Anammox to reduce aeration demand.
- Energy-efficient aeration control (real-time dissolved oxygen control).

The objective is to approach energy neutrality or energy positivity while maintaining stringent effluent standards.

8.4 Digitalization and Smart Control

Digital integration enhances process stability and efficiency [17]:

- AI-based predictive aeration control.
- Real-time monitoring of micropollutants.
- Digital twin modeling for system optimization.
- Predictive maintenance of membranes and advanced oxidation systems.

Digital tools allow dynamic adaptation to variable influent composition and reduce overdesign margins traditionally required for safety factors.

8.5 Scalability and Modular Implementation

Emerging technologies such as photocatalysis, cold plasma, hydrodynamic cavitation, and microbial fuel cells may initially be integrated in modular configurations:

- Sidestream treatment of concentrated flows.
- Targeted polishing for reuse applications.
- Decentralized satellite treatment systems.

This modular strategy reduces financial risk while allowing incremental technological adoption.

8.6 Toward Circular and Climate-Resilient Systems

Next-generation WWTPs are increasingly designed as:

- Resource recovery facilities,
- Energy management hubs,
- Water reuse platforms,
- Carbon footprint–optimized infrastructures.

Integration strategies must therefore consider life-cycle assessment (LCA), greenhouse gas emissions, and resilience to climate-driven hydraulic variability.

9. Conclusions

The focus of wastewater treatment has shifted from the removal of conventional pollutants towards integrated, multi-barrier systems designed to meet increasingly stringent environmental standards and resource recovery goals. Although activated sludge and biological nutrient removal remain fundamental to controlling organic matter and nutrients, these processes alone are inadequate for addressing persistent micropollutants, such as pharmaceuticals, perfluoroalkyl substances (PFAS), and endocrine-disrupting compounds [11,12,14]. Although conventional chlorine-based disinfection remains cost-effective for controlling pathogens, it cannot fully eliminate recalcitrant organics, highlighting the need for advanced complementary treatment technologies. These limitations are particularly significant given the widespread occurrence of micropollutants in aquatic environments at trace concentrations and their demonstrated potential to induce adverse ecological effects even at very low levels. As a result, the need for effective and scalable advanced treatment solutions becomes increasingly critical.

Advanced oxidation processes (AOPs), UV-based systems, membrane filtration and hybrid configurations effectively remove trace contaminants [4,21], but introduce trade-offs in terms of energy consumption, chemical use and operational complexity. Emerging technologies, such as hydrodynamic cavitation, photocatalysis, microbial fuel cells, forward osmosis, and cold plasma, demonstrate promising efficiencies at laboratory and pilot scales. Strategic integration of these technologies, including modular deployment and sidestream applications, offers a way to overcome limitations when scaling up, while optimising energy recovery and operational sustainability.

Regulatory developments in the European Union and the United States emphasising micropollutant control, nutrient discharge limits and energy neutrality are accelerating the adoption of advanced and hybrid treatment systems [30,31]. Compliance with these frameworks requires innovative treatment architectures combining biological, physicochemical and digital process control solutions. Digitalisation, including AI-assisted aeration control, real-time monitoring and predictive maintenance, enables operational optimisation, energy efficiency and adaptive responses to variable influent composition.

Next-generation wastewater treatment plants are expected to function as resource recovery hubs, integrating energy-positive processes, nutrient reclamation (e.g. struvite precipitation), water reuse and climate-resilient designs. Transitioning from conventional treatment to circular, digitally optimised and hybridised systems provides a practical blueprint for achieving high effluent quality, regulatory compliance and environmental sustainability, all while maintaining cost-effective operation [6,7].

Ultimately, the future of wastewater treatment will not be defined by individual technologies, but by the intelligent integration of biological, physicochemical, and digital systems into coherent, energy-efficient treatment frameworks. The ability to align treatment performance with regulatory requirements, resource recovery, and energy optimisation will determine the success of next-generation wastewater treatment plants.

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Annex A

Comparative Technical Assessment of Selected Oxidants in Wastewater Treatment

Feature	Ozone (O_3)	Hydrogen Peroxide (H_2O_2)	Zinc Peroxide (ZnO_2)	Fenton (Fe^{2+}/H_2O_2)	Chlorine-Based Compounds (Cl_2 / $NaOCl$ / $Ca(OCl)_2$)
Form	Gas (generated on-site)	Liquid	Solid powder	Liquid reagents (H_2O_2 + Fe^{2+} salt)	Gas (Cl_2) or liquid/solid hypochlorites
Toxicity	Very high (inhalation hazard)	Moderate	Low–moderate (Zn^{2+} toxicity)	Moderate–high (acidic, corrosive)	High (Cl_2 gas); moderate for hypochlorites
Handling & Storage	On-site generation; corrosion-resistant systems required	Cool storage; contamination-sensitive	Dry storage; manage Zn residues	Requires acid dosing; sludge handling; chemical storage	Cl_2 requires pressurized storage; hypochlorites degrade over time
Reactivity	Very fast; strong oxidant; indirect •OH formation	Moderate alone; strong with UV/HC/Fe^{2+}	Slow H_2O_2 release; mild oxidation	Very strong •OH generation at acidic pH	Strong selective oxidant; forms HOCl in water
Ease of Dosing	Gas injection system required	Simple liquid dosing	Slurry/solid dosing; slower response	Multi-chemical dosing (Fe^{2+} + H_2O_2 + pH control)	Simple liquid dosing (NaOCl); gas dosing more complex
Environmental Impact	Decomposes to O_2; harmful if residual persists	Decomposes to H_2O + O_2	Zn accumulation risk	Iron sludge generation; residual iron disposal	DBP formation (THMs, HAAs); aquatic toxicity if residual remains
Main Use Targets (WWTP)	Micropollutants, pharmaceuticals, color, odor	AOP precursor; industrial organics; odor	Slow-release oxidation; soil/sludge applications	Recalcitrant organics; high-strength industrial effluents	Pathogen inactivation; odor control; Fe/Mn oxidation
Implementation Cost	High CAPEX (ozone generator); moderate–high OPEX	Low CAPEX; moderate OPEX	Low CAPEX; moderate material cost	Moderate CAPEX; high chemical OPEX	Low–moderate CAPEX; low chemical cost (except Cl_2 safety systems)
Operational Limitations	Bromate formation; energy-intensive; mass transfer limits	Requires activation for strong oxidation	Limited large-scale municipal data	Requires pH ≈ 3; sludge production; not ideal for large municipal flows	DBP formation; limited micropollutant removal; dechlorination often required
Typical Removal Efficiency	70–99% for many micropollutants	Moderate alone; high in AOP (>70% organics)	Low–moderate; application-specific	High mineralization for industrial streams (>70–90% COD reduction in optimized systems)	>3–6 log pathogen removal; low for persistent micropollutants